In Vivo Monitoring of HIFU Induced Temperature Rise in Porcine Liver Using Magnetic Resonance Thermometry[1]

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1 Background

High intensity focused ultrasound (HIFU) is a noninvasive medical procedure during which a large amount of energy is deposited in a short duration, which causes sudden localized rise in tissue temperature, and ultimately, cell necrosis. In the preclinical characterization of thermal fields generated by HIFU systems, the temperature rise in an ex vivo or an in vivo tissue must be accurately measured. The temperature rise can be measured using thin wire thermocouples or magnetic resonance (MR) thermometry.

Among the two methods, thermocouples can be embedded invasively in the animal tissue, and HIFU induced temperature rise can be measured by focusing the beam on the thermocouple junction for the desired sonication time. However, the temperature rise measured using thermocouples is subject to several significant sources of error. One source of error associated with direct HIFU sonication of thermocouples is viscous-heating artifact [1]. Positioning errors represent another challenge in measuring temperature by locating beam atop a thermocouple [2]. Consequently, it has been difficult to accept that the temperature recorded by the thermocouple is the actual temperature at the focus of the HIFU beam. Therefore, there is a need for a method that can address these limitations.

Unlike the measurement of temperature using thermocouples, the MR thermometry is a noninvasive method that does not suffer from the problems of positioning error and thermal artifacts. The magnetic resonance imaging (MRI) scanner is capable of assessing the transient temperature rise across the treatment volume, as well as measuring the volume of the thermal lesion [3]. Although the MR temperature monitoring was used to evaluate the feasibility of MR-guided HIFU ablation in the liver and kidney [4], the effect of higher acoustic powers on initiation of cavitation and possible maximum temperature rise in these organs were not assessed using MR thermometry. In this study, MR thermometry was used to monitor HIFU ablations performed on in vivo porcine livers, at elevated acoustic powers of 10 W, 30 W, and 40 W to assess the temperature field where initiation of cavitation is known to occur. Temperature rise during the heating phase as well as the temperature decay during the cooling phase was acquired. The transient temperature profiles measured during the heating and cooling phases for the three powers were compared, in order to check the HIFU induced maximum temperature rise.

2 Methods

A set of HIFU ablations on in vivo porcine livers ($n = 3$) was conducted in the MR bore. Based on the MR bore dimension, an MR compatible positioning system was constructed for accurately locating the HIFU transducer vertically on the porcine liver (Fig. 1). The transducer, H102 (Sonic Concepts Inc., Bothell, WA), having a focal length of 6.26 cm, outer radius of 3.2 cm, inner radius of 1.1 cm, and frequency of 1.1 MHz, was oriented vertically and coupled to the porcine liver via a plexiglass coupling cone that was filled with degassed water (Fig. 1). The tip of the cone was placed at selected locations atop of the exposed liver surface and the lesion was formed below the tip. In order to prevent the infiltration of noise signals in the MRI room, a low-pass filter was incorporated in the electronic system [5]. Each porcine liver was ablated in three different zones using acoustic powers of 10 W, 30 W, and 40 W, keeping the sonication time same (30 s). Thus, there were a total of nine sonication zones (3 pigs × 3 sonications/pig).

During the HIFU ablation procedure, MR imaging was performed using a 3 Tesla whole body scanner (Achieva, Philips Healthcare, Best, The Netherlands). MRI-derived temperature rises were generated based on the proton resonance frequency (PRF) shift thermometry [6]. The estimate in relative temperature change ΔT, is given by

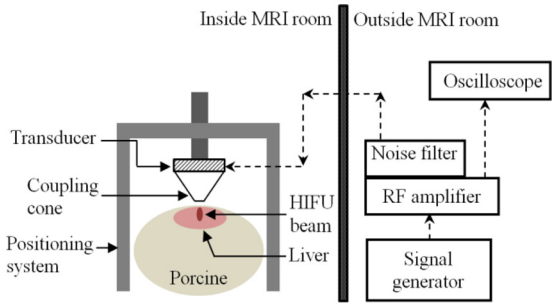

Fig. 1 Schematic of HIFU experimental setup

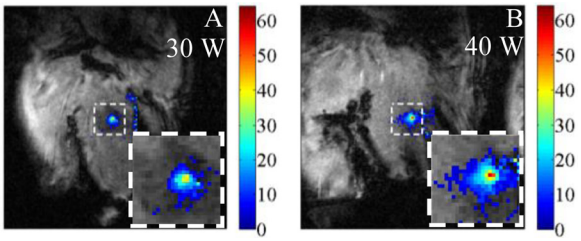

Fig. 2 Highest temperature map for the acoustic powers of (*a*) 30 W and (*b*) 40 W

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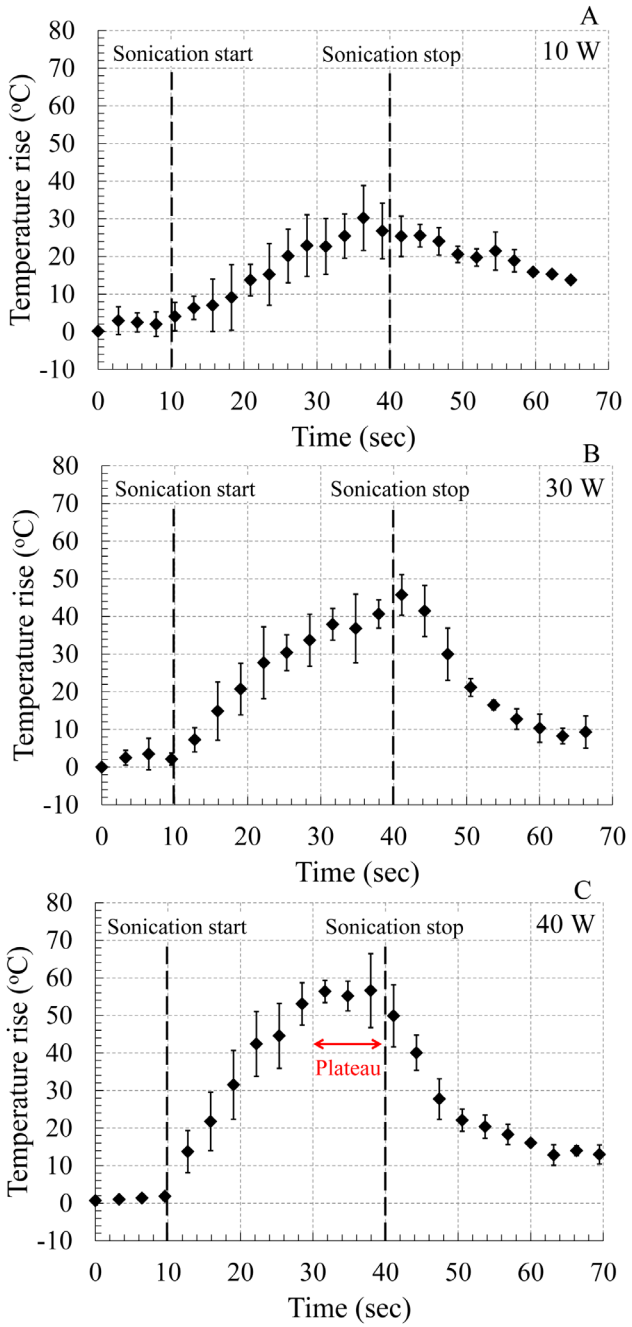

Fig. 3 HIFU induced temperature rise in porcine liver with sonication period of 30 s using acoustic powers of (*a*) 10 W, (*b*) 30 W, and (*c*) 40 W

$$\Delta T = \frac{\phi(T) - \phi(T_0)}{\gamma \alpha B_0 TE} \tag{1}$$

where $\phi(T)$ is the phase in the current image, γ is the gyromagnetic ratio, B_0 is the magnetic field strength, α is the PRF change coefficient, TE is the echo time, and $\phi(T_0)$ is the phase angle of a pixel outside the heated area, which corresponded to the base temperature. Imaging parameters for the current study were: $\gamma = 2.675 \times 10^8$ rad/s/T, $\alpha = 0.01 \times 10^{-6}$ ppm/C, $B_0 = 3.0$ T, TE = 0.01 s, number of slices = 3, and slice thickness = 3 mm. The imaging temporal resolution was 3.15 s for the acoustic powers of 30 W and 40 W while it was 2.58 s for the acoustic power of 10 W.

3 Results

The sonication process was initiated at a time of 10 s for all three powers. The presonication liver tissue temperature was 37 °C. The highest temperatures measured by MR thermometry during HIFU ablation procedure for the powers of 30 W and 40 W are shown in Figs. 2(*a*) and 2(*b*), respectively. It can be seen in Figs. 2(*a*) and 2(*b*) that the maximum temperature rise and thermal lesion volume increase with the increase in power.

Figures 3(*a*)–3(*c*) show the HIFU induced temperature rise derived from MR temperature maps, for the acoustic powers of 10 W, 30 W, and 40 W, respectively. The maximum temperature rise, which has been averaged over three trials, for each acoustic power of 10 W, 30 W, and 40 W was 30.2 ± 8.6 °C, 45.7 ± 5.4 °C, and 56.6 ± 9.8 °C, respectively. The statistical averaging of three sets of temperature data for different lesions shows some variability particularly during the heating time period (between 10 s and 40 s). For lower powers (10 W and 30 W) the peak ablation temperature was observed to be close to the end of sonication time (40 s). However, at the highest power (40 W) some anomalies in the temperature trace, e.g., plateau without a distinct peak value between 30 s and 40 s were observed (Fig. 3(*c*)). This indicates possible bubble cloud formation and the initiation of cavitation. Such a phenomenon needs further assessment. Temperature increases were also not proportional to power increases, due to the cooling effects of blood flow in the highly perfused liver.

4 Interpretation

This study shows the feasibility of MR thermometry to acquire the maximum temperature rise as well as localized cavitation during an HIFU in vivo ablation procedure. One of the advantages of using MR thermometry is that the maximum temperature rise at the HIFU beam focus can be measured accurately without any thermal artifact, which has been the major problem with the temperature measurement using thermocouples. In order to improve the accuracy of the temperature measurement, the spatial and temporal resolution of MR thermometry can be increased. Despite the limitation in increasing the spatial resolution, the location of maximum temperature rise (beam focus) can be found more accurately in comparison with the thermocouple method, which is subjected to positioning errors. For thermal dose calculation multiple thermocouple arrangement is needed whereas for MR thermometry such determination can easily be obtained without artifact and noninvasively using the temperature field from MR thermometry.

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